

Pull-through Strength of High Tensile Steel Cladding Systems*

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SUMMARY *The profiled steel roof and wall cladding systems in Australia are commonly made of very thin high tensile steels, and are crest-fixed with screw fasteners. A review of current literature and design standards indicated the need to improve the understanding of the behaviour of crest-fixed steel cladding systems under wind uplift/suction loading, in particular, the local failures. Therefore a detailed experimental study using a series of small scale tests and some two-span cladding tests was conducted to investigate the local pull-through and dimpling failures in the commonly used steel cladding systems. The applicability of the current design formulae for the pull-through strength of crest-fixed steel cladding systems was investigated first. An improved design formula was then developed in terms of the thickness and ultimate tensile strength of steel cladding material and diameter of screw head or washer. This paper presents the details of this investigation and its results. A review of current design and test methods is also included.*

1 INTRODUCTION

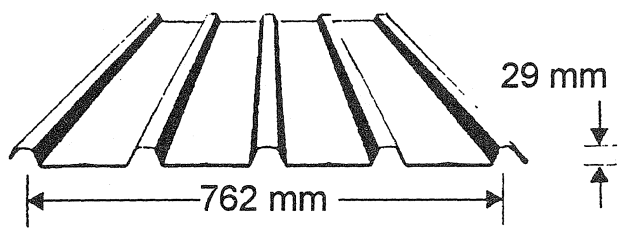
The profiled steel cladding systems in Australia (see Figures 1(a) and (b)) are commonly made of very thin high tensile steels (0.42 mm base metal thickness and G550 steel - minimum yield strength of 550 MPa), and are crest-fixed with screw fasteners (see Figure 1(c)) whilst in the USA and Europe the claddings are made of thicker lower strength steels and are valley-fixed. The thin high tensile steels have a very high yield stress (> 550 MPa), at the expense of reduced ductility (strain at failure $< 2\%$). The other major difference is the governing load case. In the USA/Europe scenario, snow loading often dominates the design of buildings. In contrast, in Australia and its neighbouring pacific countries, wind uplift/suction loading dominates the design of low-rise buildings, which suffer severe damage during high wind events such as cyclones and storms.

During high wind events, disengagement of steel roof and wall cladding systems has occurred because of local failures of their screwed connections under wind uplift/suction loading. The two common local failures are pull-out and pull-through failures. The pull-out failure has already been investigated (Mahendran and Tang, 1996). Therefore, this paper considers the pull-through failure (see Figure 2). Although the local dimpling failure shown in Figure 2(b) does not cause

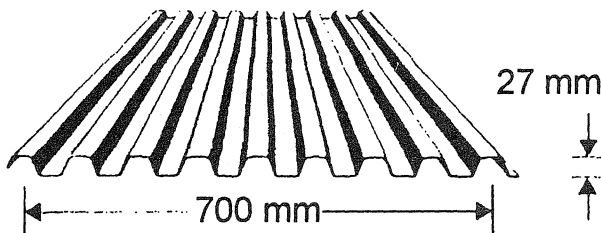
pull-through under static load conditions, fatigue cracking is initiated and accelerated during fluctuating wind loading, leading to a pull-through failure within a few cycles of loading (Mahendran, 1990a,b). Therefore this paper considers both local failures caused by splitting and dimpling as pull-through failures.

A number of researchers have already investigated the pull-through failures (Mahendran, 1990a,b, 1994, 1995a,b, Xu, 1994, Beck and Stevens, 1979). As a result, a wealth of research information is available. However, further research data is needed in order to develop reliable design formulae that can be used in design practice without the need for further testing. Thus an investigation was carried out to study the pull-through failures in profiled steel claddings using a series of small scale tests and some two-span cladding tests under static wind uplift/suction load conditions. A series of profiled steel claddings, which are commonly used in Australia (see Figure 1), was investigated for a range of screw fasteners and washers. The applicability of the American/European design formulae for pull-through strength of crest-fixed roof and wall cladding systems was investigated first. An improved formula was then developed in terms of the thickness and ultimate tensile strength of steel cladding material, and diameter of screw head or washer. This paper presents the details of this investigation and its results for the commonly used steel cladding profiles under static wind uplift / suction load conditions. A review of current design and test methods is also included.

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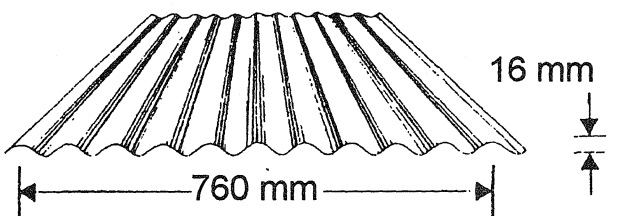


(i) Type A

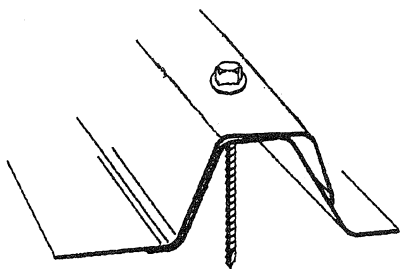


(ii) Type B

(a) Trapezoidal Profiles



(b) Corrugated Profiles



(c) Crest - fixed Cladding

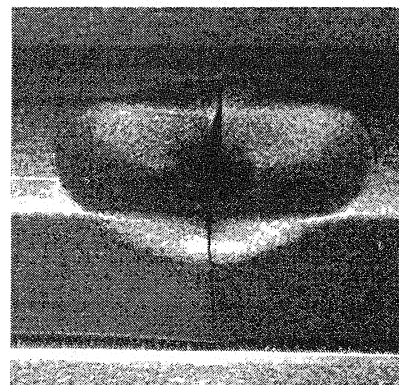
Figure 1 Standard Profiled Steel Cladding Systems used in Australia

2 REVIEW OF CURRENT DESIGN AND TEST METHODS

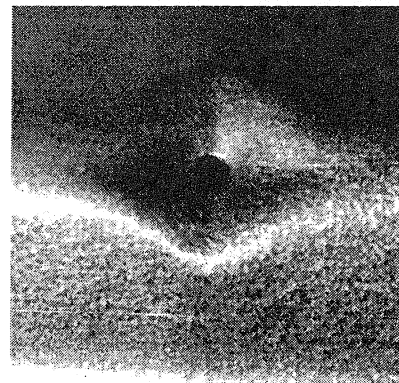
The American (AISI, 1989) and European provisions (Eurocode 3, 1992) give design formulae for mechanically fastened connections in tension in cold-formed steel sheeting and sections. The pull-through strength, F_{ov} , is calculated as follows:

$$\text{AISI (1989)} \quad F_{ov} = 1.5 t d f_u \quad (1a)$$

$$\text{Eurocode 3 (1992)} \quad F_{ov} = 1.1 t d_w f_y \quad (1b)$$



(a) Local Splitting Failure



(b) Local Dimpling Failure

Figure 2 Typical Pull-through Failures of Profiled Steel Cladding Systems

where t = thickness of steel cladding material
 d = larger value of the screw head or the washer diameter ≤ 12.7 mm (1/2 inch)
 d_w = the washer diameter
 f_y, f_u = yield and ultimate tensile strength of steel

For G550 steels of thickness less than 0.9 mm, it is recommended that 75% of the minimum specified strength be used in Equations 1(a) and 1(b). These equations can be used with any consistent unit system. Pekoz (1990) and Toma et al. (1993) present the background to the American and European equations, respectively.

As previous Australian design codes do not recommend any design formula, the design for the pull-through failures of screwed connections in tension has been entirely based on laboratory experiments. Nevertheless, Equation (1a) has now been included in the new Limit States Cold-formed Steel Structures Code AS4600 (SAA, 1996). This design formula was developed for conventional fasteners and thicker mild steel and therefore there is a need to verify the applicability of this formula for Australian crest-fixed steel cladding systems.

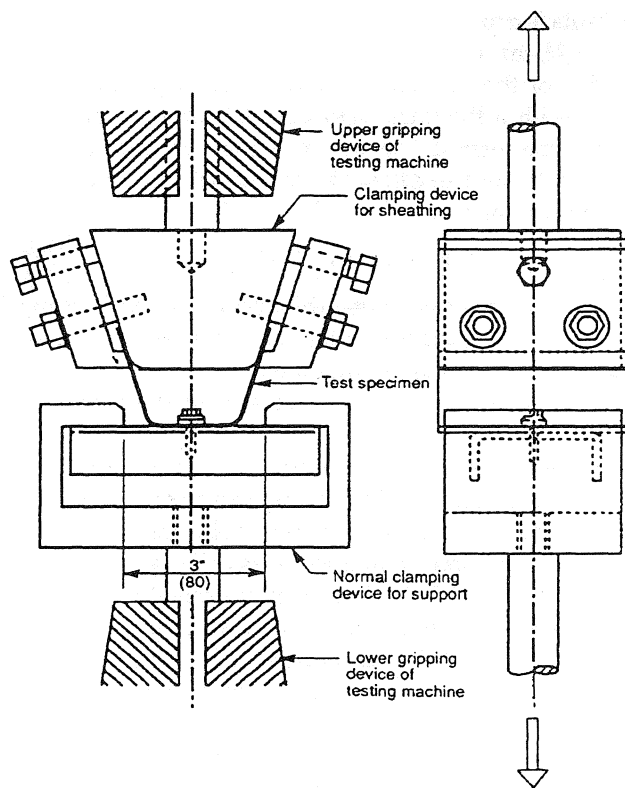


Figure 3 Standard Tension Test Method (AISI, 1992)

As an alternative to the design method, the American and European specifications (AISI, 1989, Eurocode, 1992) recommend four different, but “considered to be equivalent” tension test methods to determine the pull-through strength of mechanically fastened connections in tension loading in cold-formed steel sheeting and sections. They were mainly developed for valley-fixed profiled steel claddings. The first three methods use small scale models, whereas the fourth method uses a large scale model of cladding. The first test method, the standard test method which the American and European provisions recommended to be used whenever possible, may not be correct as it uses a standard U-shaped specimen for all profiles (see Figure 3). A review of the American and European test methods showed that these methods cannot be used directly for the determination of pull-through strength of crest-fixed claddings as they do not take into account the effects of profile geometry (Mahendran, 1995b). They model only the tension loading in the fastener, and do not simulate the longitudinal and transverse bending and membrane deformations that occur around the fastener hole. Therefore an alternative small scale test method that eliminated these shortcomings (Figure 4) was proposed by Mahendran (1994). The specific standard test method recommended by AISI (1992) was modified by inserting cross-battens to allow for sheathing to bend in both longitudinal and transverse directions around the fastener hole. Since pull-through failures are highly localised around the screw holes (see Figure 2), a small scale sheeting around the screw hole was chosen. The recommended test specimen of approximately 240 mm

× 240 mm was bolted to a small wooden frame of four 25 mm × 50 mm members. The width of the specimen between the bolts in transverse direction was the pitch of the cladding profile including the rib. A long screw fastener with a load cell attached to it was located at the centre of the specimen. The specimen was then loaded with a tension force by using a simple hand-tightening procedure, and the applied load was measured by the load cell. This improved small scale test method is considered to simulate the local splitting/dimpling failure at the fastened crest of the sheeting, and the tension force in the screw fastener at failure will be the required failure load. The use of this small scale test method was validated by comparing its results with those from two-span cladding tests of the current Australian cladding profiles shown in Figure 1 (Mahendran, 1994). However, its accuracy is not known for other cladding profiles, and care must be taken in using this small scale test method.

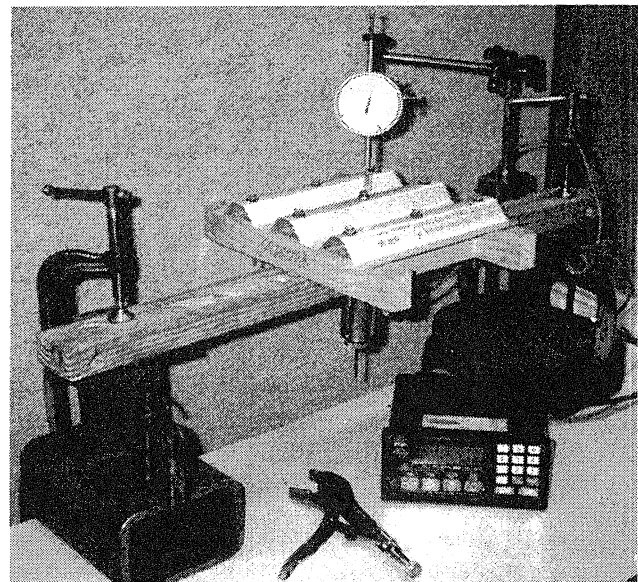


Figure 4 Small Scale Cladding Test Method

In the past, the U-tension, cross tension and plate methods have also been used for testing single point fasteners. Note that these methods were used for both pull-out and pull-through strength determinations. Macindoe and Hanks (1994) reviewed these test methods and recommended the popular cross-tension method (see Figure 5). This cross-tension test method is now included in the new limit states code of Cold-formed Steel Structures, AS4600 (SAA, 1996). However, it is unlikely that the cross-tension test method can predict the pull-through strength of a crest-fixed steel cladding system.

Macindoe et al. (1995) used the cross-tension test method to obtain data from a large number of pull-through tests, based on which they modified the design formula (Equation 1(a)) to better model the observed behaviour. Equation 2 gives their modified

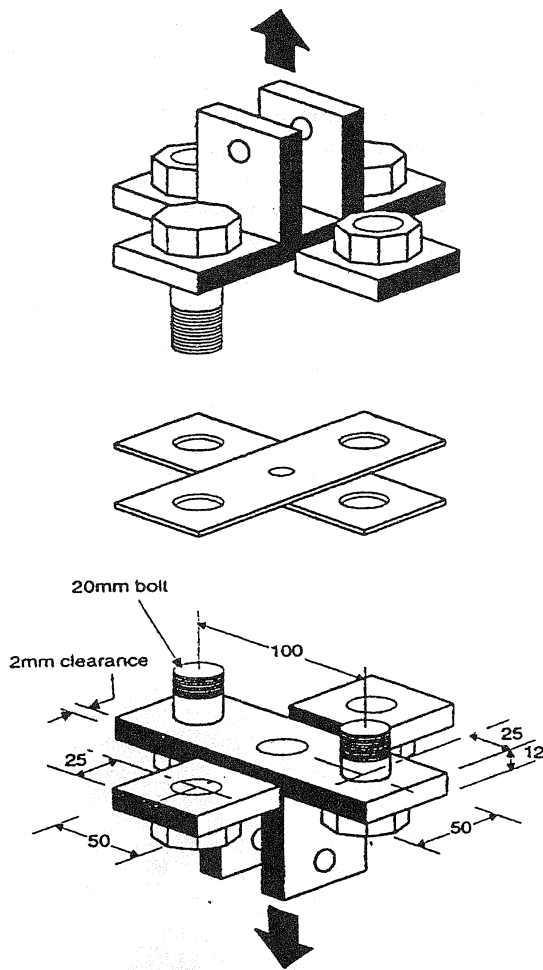


Figure 5 Cross-Tension Test Method (Macindoe et al., 1995)

formula for pull-through strength F_{ov} . By using the term $f_u^{0.5}$, this equation eliminates the need for the use of 75% of the specified minimum strength for G550 steels with a thickness less than 0.9 mm. It also includes the term $d^{0.5}$ to improve the correlation with test results and to allow the values of d in excess of 12.7 mm to be used.

$$F_{ov} = 80 \sqrt{(t^{2.6} d f_u)} \quad (2)$$

where t = base metal thickness of steel cladding
 d = larger value of the screw head or washer diameter
 f_u = ultimate tensile strength of steel

A two-span steel cladding assembly with simply supported ends was also commonly used in the past investigations. The uniform wind uplift pressure was simulated by either using air bags or layers of bricks (Mahendran, 1990a,b). In the latter case, the cladding was set-up as inverted and ribs were first filled with sand (Figure 6). When the pressure in the air bags or the brick loading was increased the cladding underwent significant cross-sectional distortion and then failed locally around the central support fasteners. The central support screw fasteners pulled-through the trapezoidal claddings due to the splitting of sheeting at the edge of the fastener hole whereas a local dimpling failure of the crests occurred for corrugated claddings (see Figure 2). The central support reaction was measured using two load cells located at the ends of the central support, which enabled the determination of the average pull-through or local dimpling failure load per fastener at the critical central support (Figure 6). Although the two-span cladding test meth-

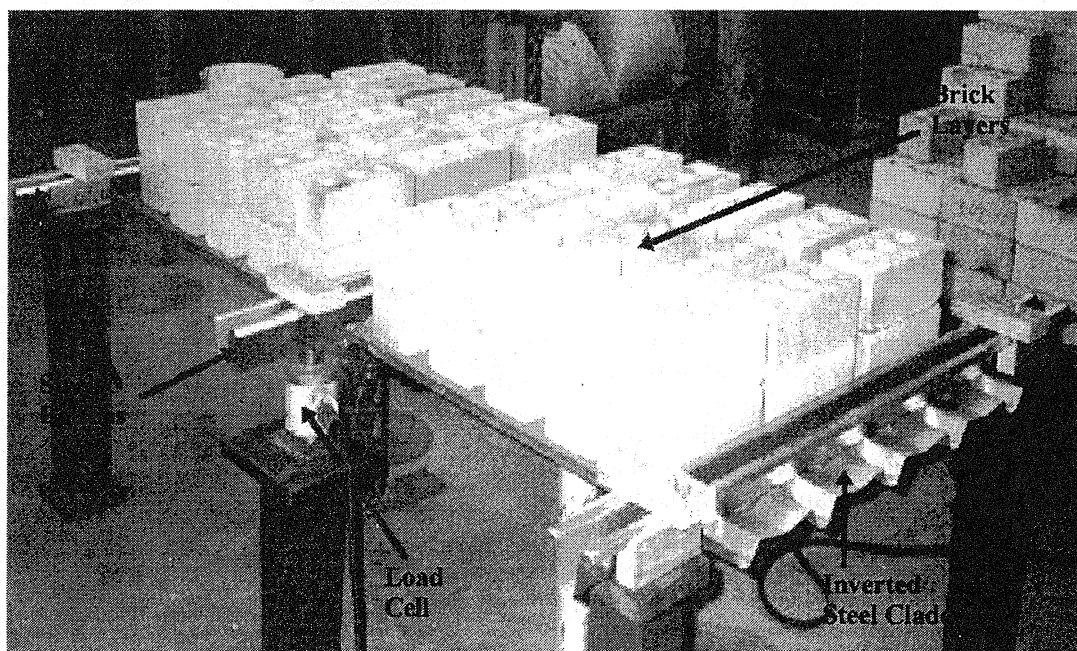


Figure 6 Two-span Cladding Tests using Brick Loading

ods model the steel cladding system and loading more accurately, the simpler small scale test methods are to be preferred if they are adequate.

Mahendran (1994) conducted finite element analyses (FEA) and experiments of two-span crest-fixed steel roof claddings. Both FEA and experiments indicated that large membrane stresses were present in the longitudinal direction, which reached yielding. This explained the transverse fracture observed at the fastener hole as the high tensile steel used had limited ductility. It was noted that there was no buckling or global yielding of the section elsewhere in the sheeting, which indicated that the cladding strength was determined by this localised pull-through or dimpling failure at the crests around the fastener hole. It is therefore recommended that the design of steel cladding systems is based on the local pull-through or dimpling strength of their screwed connections as the load per fastener at the critical central support is the most important parameter. Based on this investigation, a simple design formula was recommended for the strength of screwed connections in the common roof claddings under wind uplift loading (Mahendran, 1994). Equation 3 gives this formula for pull-through strength F_{ov} of crest-fixed steel cladding systems. By using the term $f_u^{1/3}$, this equation also eliminates the need for the use of 75% of the specified minimum strength for G550 steels with a thickness less than 0.9 mm.

$$F_{ov} = c t^2 f_u^{1/3} \quad (3)$$

where c is a coefficient that depends on the geometry of steel cladding profiles (0.74 and 0.66 for Trapezoidal Type A and Type B Claddings, and 0.45 for Corrugated claddings), and t and f_u are as defined in Equation 2.

3 EXPERIMENTAL PROGRAM

The use of finite element analyses to predict pull-through failure associated with splitting is inaccurate due to the unavailability of a reliable criterion for splitting. Therefore, it was decided to use laboratory experiments of cladding systems. Obviously, the small scale test method recommended by Mahendran (1994) and shown in Figure 4 is very simple to use and enables a large number of pull-through tests to be completed with limited resources in a short period of time. Thus this investigation adopted this small scale test method and a series of pull-through tests were conducted for a range of profiled steel claddings and screw fasteners, which are commonly used in the Australian building industry. The G550 grade steel claddings including the trapezoidal profiles (both Types A and B) and the corrugated profiles with different thicknesses from 0.42 to 0.60 mm BMT (Base Metal Thickness) were tested (Figure 1). The screw fasteners included screw sizes of No. 12 and 14 (both nominal screw head diameters of 12.7 mm). The screw head d_h or washer diameter d_w was varied from 12.7 to 22.0 mm. A larger hole diameter d_o of 9.0 mm was

also used in order to simulate a larger screw shaft size. Thus the effects of different screw shaft sizes (d_o from 5.2 mm to 9.0 mm) were also studied in this manner. Figure 7 and Table I give the details of screw fasteners used in this investigation, whereas Figure 1 has already given the details of steel claddings. A series of tests was conducted for a combination of each type of screw fastener in Table I and each cladding shown in Figure 1, resulting in a total of 103 experiments. Test specimens of approximately 240 mm × 240 mm were loaded by the simple hand tightening method until the sheeting split at the fastener hole (see Figure 4). The load decreased very rapidly after the sheeting had split or dimpled at the screwed crests, and thus the pull-through or local dimpling load was taken as the maximum load observed during the test.

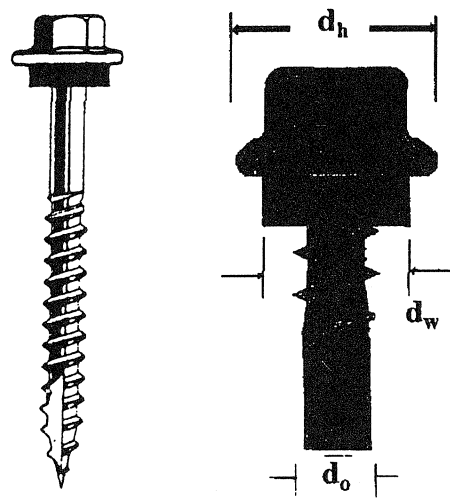


Figure 7 Screw Fasteners

4 DISCUSSION OF EXPERIMENTAL RESULTS

Table II presents the experimental pull-through and local dimpling failure loads for trapezoidal cladding – Type A. Other results are given in Tang and Mahendran (1998). In this investigation, tests were also conducted on two-span cladding models and valley-fixed small scale models. In the two-span tests, severe cross-sectional distortions of the profile were observed. Combined membrane and bending actions in both longitudinal and transverse directions were observed in the region around the fastener holes on both two-span and small scale cladding specimens. As observed by Mahendran (1994), the dominant membrane tensile stresses in the longitudinal direction led to the transverse splitting in the cladding made of G550 steel with very limited ductility (about 2%). The splitting then grew rapidly and allowed the fasteners to pull-through the sheeting.

It must be noted that a local dimpling failure (without any splitting) occurred for corrugated claddings and some trapezoidal claddings (see Figures 2(b) and 8(c)). Although there was some reserve strength beyond this

Table I
Details of Screw Fasteners

Screw Size	Screw Head* d_h (mm)	Washer* d_w (mm)	Hole/Shaft Diameter d_o (mm)	
			Nominal	Measured
No.14 Type-17	12.7 (1/2 in)	14.5	6.4	5.2
			9.0	9.0
		17.5	6.4	5.2
		20.0		
No.12 Type-17	12.7 (1/2 in)	14.5	5.4	4.8
			9.0	9.0
		17.5	5.4	4.8
		20.0		
		22.0		

Note: * : Nominal and measured diameters are the same

Table II
Experimental Results for Crest-fixed Trapezoidal (Type A) Cladding

G550 Steel, f_y / f_u (MPa)			Screw Diameter		Failure Load	Average
t (mm)	Measured	Specified	d (mm)	d_o (mm)	(N/fastener)	(N/f)
0.42	717 / 721	550 / 550	14.5	5.2	1353, 1403, 1302, 1204, 1302, 1302, 1301, 1300, 1290, 1310, 1360, 1420, 1356	1323
			14.5	9.0	1452, 1301, 1404, 1452, 1425, 1302,	1389
			17.5	5.2	1603, 1551, 1601, 1550, 1401, 1502	1535
			20.0	5.2	1607, 1601, 1510, 1480, 1540	1548
			22.0	5.2	1601, 1604	1603
0.48	717 / 721	550 / 550	14.5	5.2	1750, 1790, 1740, 1880, 1830	1798
			20.0	5.2	2070, 2080, 2070	1548

Notes: 1. d = Larger value of the screw head or the washer diameter
2. d_o = the screw shaft or hole diameter

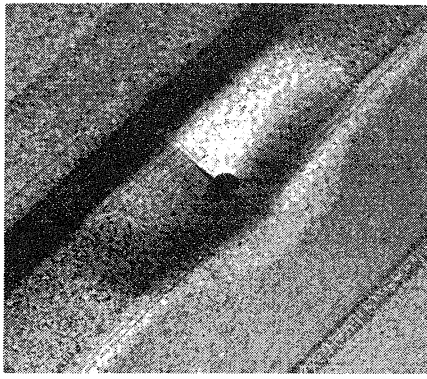
dimpling failure in the two-span cladding tests, it cannot be included for design purposes. The localised deformations and the splitting failure occurred in most of the tests with different screw head/washer and hole sizes. Figures 8 (a) to (d) show these failures for various screw head/washer and hole sizes.

The pull-through or local dimpling strength was very much dependent on the thickness t of the steel claddings. When the shaft/hole diameter d_o of screw fasteners was changed (ie. 5.2, 9.0 mm), the strength of both crest-fixed and valley-fixed claddings changed only marginally for all three profiles. However, when the diameter of screw head or washer (d) was changed from 14.5 to 17.5, 20.0 and 22.0 mm, there was significant increase in the pull-through strength

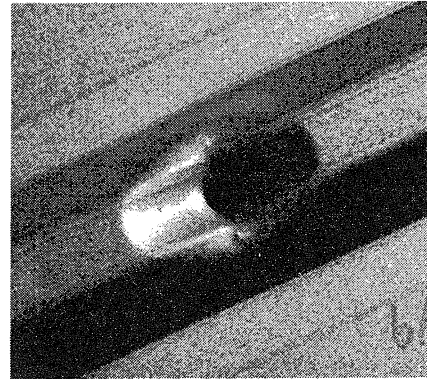
of screwed connections for trapezoidal Type A cladding, and some increase for trapezoidal Type B cladding. For corrugated cladding, increase in diameter of the screw head/washer (d) may not affect the local dimpling strength as the contact area between the flat bottom of the screw head/washer and the curved corrugated surface of the cladding does not increase at all. This is why the diameter of screw head/washer was not included in the formula recommended by Mahendran (1994) (Equation 3).

4.1 Comparison of Test to Predicted Values based on the Current Design Formula

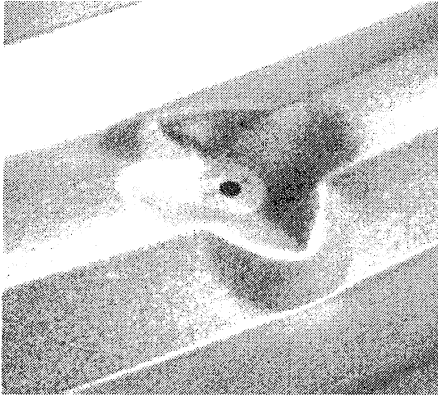
The pull-through failure loads from experiments on trapezoidal claddings (Type A and Type B) were com-



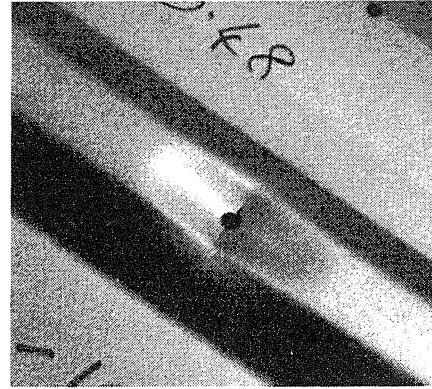
(a) Conventional



(b) Bigger Screw Hole



(c) Bigger Washer



(d) Thicker Cladding

Figure 8 Typical Pull-through Failures for Different Screw Fasteners and Cladding

Table III

Test to Predicted Values Based on Current Design Formula and Measured Properties

Fastener Fixity Type	Screw Diameter d (mm)	Trapezoidal Claddings					
		Type A + Type B		Type A		Type B	
		Mean	COV	Mean	COV	Mean	COV
Crest-fixed	Actual	0.19	0.14	0.20	0.11	0.18	0.14
	12.7	0.24	0.10	0.26	0.10	0.23	0.07
Valley-fixed	Actual	0.52	0.11	0.53	0.11	0.51	0.11
	12.7	0.68	0.05	0.69	0.05	0.68	0.05

Notes: 1. d = Larger value of the screw head or the washer diameter

2. COV = Coefficient of Variation

pared with the predictions from the current design formula given by Equation 1(a) using both the measured and specified (nominal) properties of the steel and screw fasteners. Tables III and IV present these comparisons in that order for each group of steel cladding systems. In Table IV, 75% of the specified minimum strength of G550 steel (412 MPa) was used for G550 steels of thickness less than 0.9 mm. This is according to the current American code (AISI, 1989) and the new Australian code AS4600 (SAA, 1996).

Since the screw head or washer diameter used in the experiments was greater than or equal to 12.7 mm,

the current design formula requires the use of 12.7 mm for d in Equation 1(a) for all the screw fasteners used in this study. This implies that the predicted loads would vary only with the thickness t (0.42 and 0.48 mm) as the ultimate tensile strength f_u of steel was also the same for all the experiments (Measured value = 721 MPa, specified value = 550 MPa). However, experimental results varied significantly with diameter d. Therefore, actual diameter was also used in Equation 1(a) to calculate the loads from the current design formula for comparison with experimental results in Tables III and IV.

Table IV
Test to Predicted Values Based on Current Design Formula and Specified Properties

Fastener Fixity Type	Screw Diameter d (mm)	Trapezoidal Claddings					
		Type A + Type B		Type A		Type B	
		Mean	COV	Mean	COV	Mean	COV
Crest-fixed	Actual	0.33	0.14	0.35	0.11	0.31	0.14
	12.7	0.42	0.10	0.45	0.10	0.40	0.07
Valley-fixed	Actual	0.92	0.11	0.94	0.11	0.90	0.11
	12.7	1.19	0.05	1.20	0.05	1.19	0.05

As seen in Table III results, the mean Test to Predicted value is extremely low for all claddings fixed on the crests. It reveals the inadequacy of the current design formula in predicting the pull-through or local dimpling failure loads of crest-fixed cladding systems. It must be noted that the American design formula was developed only for pull-through failures (not local dimpling). The mean Test to Predicted values are less than 0.24 for all crest-fixed claddings. The values are higher for valley-fixed claddings, but are only about 0.68. These results were unexpected as the current design formula was expected to predict the pull-through strength of valley-fixed claddings adequately. Inadequacy of current design formula in this instance can be attributed to the fact that it was developed based on test results for thicker lower grade steels with adequate ductility. In this investigation, the claddings were made of high tensile steel (G550) with reduced ductility and hence the lower test to predicted values resulted for even the valley-fixed claddings. This problem can be overcome if 75% of the specified minimum strength of G550 steel is used. When this was done, Table IV results using specified properties reveal that the mean values have increased but still less than 1.0 for all cases except for valley-fixed claddings with conventional screw fasteners. Therefore the use of 75% of specified tensile strength for G550 steel less than 0.9 mm is preferred, and appears to be suitable to predict the pull-through strengths for valley-fixed claddings only.

The use of an upper limit of 12.7 mm for diameter d in Equation 1(a) does not appear to be correct as test failure loads increased with increasing d beyond 12.7 mm. However, further experimental evidence is needed to confirm this beyond any doubt.

The pull-through test results from Macindoe et al. (1995) in relation to the current design formula gave much higher mean Test to Predicted values in all cases; for example, Macindoe et al.'s results gave a mean value of 0.60 for G550 steels with thickness of 0.42 mm (BMT) compared with 0.19 in this investigation. This implies that the general test method of using cross tension specimens could have produced unconservative results compared with the method used in this investigation to model the actual pull-through failures in profiled steel claddings. These ob-

servations also indicate that the cross-tension test method may produce unconservative results for pull-through strengths of crest-fixed steel cladding systems, but may be adequate for valley-fixed claddings.

4.2 Comparison of Test to Predicted Values Based on the Modified Design Formula of Macindoe et al. (1995)

The pull-through failure load results from tests on trapezoidal claddings were compared with the predictions from Macindoe et al.'s (1995) modified design formula (Equation 2) using both the measured and specified (nominal) properties of steel and screw fasteners (Tables V and VI). In Table VI, 75% of the specified minimum strength of G550 steel (412 MPa) was not used for G550 steels of thickness less than 0.9 mm as recommended by Macindoe et al. (1995). Unlike the current design formula, Macindoe et al.'s formula does not specify an upper limit for d. Hence actual values of diameter d were used in Tables V and VI.

As seen in the results in Table V, the mean Test to Predicted values give values higher than 1.37 for all cases of valley-fixed claddings, but lower values for crest-fixed claddings, which reveals that the modified design formula may only be suitable in predicting the pull-through failure loads of valley-fixed claddings. As for the current design formula (Equation 1(a)), the Macindoe et al.'s modified formula is also inadequate in determining the pull-through strength of crest-fixed steel claddings.

Table VI results using specified properties reveal that the mean values have increased to more than 1.57 for valley-fixed claddings. It may not be necessary to use the 75% of specified tensile strength for G550 steel of thickness less than 0.9 mm with the modified formula.

4.3 Comparison of Test to Predicted Values Based on Equation 3 (Mahendran, 1994)

The pull-through failure load results from tests on crest-fixed steel claddings were compared with the predicted values from the design formula recommended by Mahendran (1994) (Equation 3). Results

Table V
Test to Predicted Values Based on Macindoe et al.'s Modified Design
Formula and Measured Properties

Fastener Fixity Type	Screw Diameter d (mm)	Trapezoidal Claddings					
		Type A + Type B		Type A		Type B	
		Mean	COV	Mean	COV	Mean	COV
Crest-fixed	Actual	0.49	0.09	0.52	0.06	0.46	0.07
Valley-fixed	Actual	1.39	0.05	1.41	0.06	1.37	0.05

Note: d = Larger value of the screw head or the washer diameter

Table VI
Test to Predicted Values Based on
Macindoe et al.'s Modified Design Formula and Specified Properties

Fastener Fixity Type	Screw Diameter d (mm)	Trapezoidal Claddings					
		Type A + Type B		Type A		Type B	
		Mean	COV	Mean	COV	Mean	COV
Crest-fixed	Actual	0.56	0.09	0.60	0.06	0.53	0.07
Valley-fixed	Actual	1.59	0.05	1.61	0.06	1.57	0.05

for corrugated claddings were included as Equation 3 was also derived for these claddings. In general, the other formulae were considered applicable to trapezoidal claddings only. Table VII presents these comparisons. In the case of specified properties of Table VII, 75% of the specified minimum strength of G550 steel (412 MPa) was not used for G550 steels of thickness less than 0.9 mm. This is because this formula also uses a term $f_u^{1/3}$.

As seen in Table VII, the mean Test to Predicted values are greater than 1.0 for all cases of crest-fixed claddings with all groups of screw fasteners. For corrugated claddings, the mean test to predicted values are less than 1.0 (0.84) due to the use of lower quality corrugated claddings. Local dimpling failure loads were found to be very sensitive to the geometry of the profile used in the tests. When using specified properties, the mean Test to Predicted values produce very high values (ie. more than 1.34) for trapezoidal claddings. This reveals that the design formula given by Equation 3 may imply high level of conservativeness for profiled steel claddings. However this formula does not include the effects of screw fastener or washer diameter d in predicting the pull-through failure loads. Hence it must be considered inadequate at least for trapezoidal Type A claddings for which there is significant increase in the pull-through strength of screwed connections with increasing screw head/washer diameter.

4.4 Comparison of Test to Predicted Values Based on New Design Formulae

Equation 3 was based on parametric studies using FEA (Mahendran, 1994). The relationships between F_{ov} and each parameter t and f_u were derived independently

assuming no interaction (ie. $F_{ov} \propto t^2$, $F_{ov} \propto f_u^{1/3}$). The final formula was obtained approximately by assembling the individual relationships and finding an appropriate constant c. In this investigation, attempts were made to improve the accuracy of Equation 3. Firstly, all the parameters were considered together in the derivation of the design formula. Secondly, the larger value of the screw head or the washer diameter, d, was included in the formula.

$$F_{ov} \text{ (in kN)} = c d^\alpha t^\beta f_u^{1/3} \quad (4a)$$

$$\text{or} \quad F_{ov} \text{ (in kN)} = c d^\alpha t^\beta f_u^\chi \quad (4b)$$

where c, α , β , χ = constant and t, d, f_u are in mm and MPa units.

Equation 4(a) was first considered as a simple extension of Equation 3 by including d^α , but keeping the same t^2 and $f_u^{1/3}$ terms. Subsequently, Equation 4(b) was developed as a general equation with different power coefficients for t and f_u . Unlike the method used by Mahendran (1994), the constants of c, α , β , and χ were determined by considering all the parameters simultaneously. The "Solver" in Microsoft Excel, which is based on the method of least squares, was used to obtain the best equation that fits the test data. These constants are given in Table VIII. The local dimpling or pull-through failure loads were predicted well by both Equations 4(a) and 4(b) using both the measured and specified (nominal) properties of steel and screw fasteners. It is unnecessary to impose an upper limit for d as in the current design formula. Hence, only the actual values of diameter d were used in Table VIII.

For corrugated claddings, initial analyses gave an α value of 0.05. This confirms the experimental observation that the local dimpling load of corrugated clad-

Table VII
Test to Predicted Values Based on
Mahendran's Design Formula (1994) for Crest-fixed Claddings

Material Property	Trapezoidal Type A		Trapezoidal Type B		Corrugated	
	Mean	COV	Mean	COV	Mean	COV
Measured	1.23	0.08	1.24	0.06	0.84	0.07
Specified	1.34	0.08	1.36	0.06	0.92	0.07

Table VIII
Test to Predicted Values Based on
the Improved Design Formulae for Crest-fixed claddings

Eq. 4a	Measured Properties						Specified Properties					
Profile	c	α	β	χ	Mean	COV	c	α	β	χ	Mean	COV
Trapezoidal Type A	0.25	0.45	2.00	1/3	1.03	0.05	0.25	0.45	2.00	1/3	1.13	0.05
Trapezoidal Type B	0.45	0.20	2.00	1/3	1.03	0.05	0.45	0.20	2.00	1/3	1.13	0.05
Corrugated	0.38	0.00	2.00	1/3	1.00	0.07	0.38	0.00	2.00	1/3	1.10	0.07
Eq. 4b	Measured Properties						Specified Properties					
Profile	c	α	β	χ	Mean	COV	c	α	β	χ	Mean	COV
Trapezoidal Type A	0.22	0.40	2.20	0.40	1.03	0.07	0.22	0.40	2.20	0.40	1.15	0.05
Trapezoidal Type B	0.23	0.20	1.70	0.40	1.02	0.05	0.23	0.20	1.70	0.40	1.13	0.05
Corrugated	0.27	0.00	2.10	0.40	0.99	0.07	0.27	0.00	2.10	0.40	1.10	0.07

ding does not depend on the screw head/washer diameter. Therefore, the α value was then forced to be zero, which still gave good mean values of 1.0 and 0.99 when measured properties were used. For both the improved equations (Equations 4(a) and 4(b)), the mean Test to Predicted values and coefficient of variation (COV) values were all calculated and are included in Table VIII.

As seen in Table VIII, the mean Test to Predicted values are about 1.0 and tend to be more uniform across all the cases of crest-fixed claddings while the coefficients of variation are less than 0.07. When using specified properties, the mean Test to Predicted values increased, but are less conservative than Equation 3. This means that the improved design formulae (Equations 4(a) and 4(b)) provide a greater accuracy in predicting the local dimpling and pull-through strength of crest-fixed profiled steel cladding systems. However, since these design formulae were derived based on small scale model testing, two-span cladding tests were also conducted to validate them.

A test set-up using brick loading as in Figure 6 was used to test 900 mm span trapezoidal claddings – Type A and B. The measured central support reaction was used to determine the average load per fastener at which the central support fasteners pulled through or dimpled. The weight of bricks used was also used to check the measured load per fastener. Table IX com-

pares these results with predictions from Equations 4(a) and 4(b). Both equations are able to predict the pull-through strength of trapezoidal roofing reasonably well as seen in this table.

In summary, improved design formulae have been derived for the three commonly used claddings based on small scale model testing. These formulae are given by Equation 4(a) where c and α values are 0.25 and 0.45 for trapezoidal Type A cladding, 0.45 and 0.20 for trapezoidal Type B cladding, and 0.38 and 0.0 for corrugated cladding. Alternatively Equation 4(b) can be used where c , α , β , and χ values are 0.22, 0.40, 2.20 and 0.40 for trapezoidal Type A cladding, 0.23, 0.20, 1.70 and 0.40 for trapezoidal Type B cladding and 0.27, 0.0, 2.10 and 0.40 for corrugated cladding, respectively. However, it must be noted that the pull-through strength depends on the geometry of the cladding profile. Therefore this design equation must be further improved to include relevant geometrical parameters if its applicability is to be extended to other profiles.

4.5 Capacity Reduction Factors for the Pull-through Strength of Screwed Connections in Steel Claddings

The proposed equations mentioned in this paper could predict the average pull-through strengths based on the limited number of test data. The actual pull-

Table IX
Comparison of Predicted Results from Equations 4(a) and (b) with
Two-span Cladding Test Results

G550 Steel			Screw Diameter		Failure Load per Fastener (N)			
Cladg.	t	Measured	d	do	Small	Two-span	Equn.	Equn.
Type	(mm)	f_u	(mm)	(mm)	scale test	test	4(a)	4(b)
Trape- zoidal Type A	0.42	721	14.5	6.3	1323	1365	1317	1322
	0.42	721	14.5	7.5	-	1300	1317	1322
	0.42	721	14.5	9.0	1389	-	1317	1322
	0.42	721	15.6	6.3	-	1410	1361	1361
	0.42	721	17.5	6.3	1535	1470	1434	1426
	0.42	721	20.0	6.3	1548	1540	1522	1504
Trape- zoidal Type B	0.42	721	14.5	6.3	1297	1235	1215	1249
	0.42	721	15.6	6.3	-	1295	1233	1268
	0.42	721	17.5	6.3	1320	1310	1262	1297
	0.42	721	20.0	6.3	1337	1355	1296	1332

Note: d = Larger value of the screw head or the washer diameter

through strength of a real connection can be considerably less than the value predicted by these equations because of the expected variations in material, fabrication and loading effects. Therefore a capacity reduction factor commonly used in design codes should be recommended for the pull-through strength predicted by these equations.

The American Cold-formed Steel Structures Code (AISI, 1992) recommends a statistical model for the determination of capacity reduction factors from testing. This model accounts for the variations in material, fabrication and load effect. A modified version of this model with conservative values was recommended by Pekoz (1990) for screwed connections. This model was used in the new Australian Cold-formed Steel Structures code (Macindoe et al., 1995). By using some of the recommended parameters such as the mean and COV of material factor (1.1, 0.1), mean and COV of fabrication factor (1.0, 0.1), and COV of load effect (0.21), this model leads to the following equation for the capacity reduction factor ϕ .

$$\phi = 1.65 P_m \exp(-\beta_0 \sqrt{0.0641 + C_p V_p^2}) \quad (5)$$

where β_0 = Target Reliability Index = 3.5 for connections

C_p = Correction Factor depending on the number of tests $N = (N-1)/(N-3)$

P_m = Mean Value of the Tested to Predicted Load Ratio

V_p = Coefficient of Variation of the Tested to Predicted Load Ratio

Equation 5 was used to calculate the ϕ factor for the four design formulae (Equations 1(a), 2, 3 and 4) considered in Sections 4.1 to 4.4, respectively. Table X shows these calculations and the final ϕ factor for Equations 4(a) and (b). Other results are given in Tang and Mahendran (1998).

Comparison of the results in Tables III to VIII clearly indicated that the improved formulae Equations 4(a) and (b) are neither unconservative (mean < 1.0) nor too conservative (mean > 1.0). The mean Test to Predicted values are in the range of 0.99 to 1.03. The coefficient of variation is on average less than 0.07 and fairly uniform across different profiles whereas the other formulae produced a bigger scatter. A comparison of average maximum and minimum errors for the different formulae confirms that Equations 4(a) and (b) produce much less errors than all other formulae. Based on these observations and previous results, Equation 4(a) or 4(b) with a capacity reduction factor of 0.60 (see Table X) is recommended for determining the pull-through or local dimpling strength of crest-fixed profiled steel claddings made of G550 steel.

Table X
Capacity Reduction Factors Φ for
the Improved Design Formulae

Eq. 4a	No. of	Measured Properties		
Profiles	Tests	Mean	COV	Φ
Type A	40	1.03	0.05	0.69
Type B	44	1.03	0.05	0.69
Corrugated	21	1.00	0.07	0.66
Eq. 4b	No. of	Measured Properties		
Profiles	Tests	Mean	COV	Φ
Type A	40	1.03	0.07	0.68
Type B	44	1.02	0.05	0.68
Corrugated	21	0.99	0.07	0.65

Although steel claddings and screw fasteners used in this investigation were obtained from particular manufacturers, results should be applicable to most standard steel cladding profiles and screw fasteners provided they comply with the respective specifications for the steel claddings and screw fasteners used in this investigation.

5 CONCLUSIONS AND RECOMMENDATIONS

This paper has presented the details of an experimental investigation into the local pull-through and dimpling failures of crest-fixed thin high tensile steel claddings that are commonly used in Australia. Experimental results based on a large number of small scale sheeting models were used to review the currently available design formulae and to develop a new design formula. The conclusions and recommendations of this investigation are as follows.

1. The current design formula (Equation 1) is incapable of predicting the pull-through strength of crest-fixed steel cladding systems considered in this investigation. The current design formula with an upper limit of 12.7 mm for screw head/washer diameter and the use of 75% of specified tensile strength for G550 steel less than 0.9 mm might give conservative results only for valley-fixed cladding systems.
2. A modified design formula (Equation 2) recommended by Macindoe et al. (1995) appears to be more suitable than the current design formula for the pull-through strength of crest-fixed steel cladding systems, but is also inadequate. However, it is conservative for valley-fixed steel cladding systems.
3. The general cross-tension test method proposed in the Australian Cold-formed Steel Structures Code AS4600-1996 may not produce conservative/accurate test results for the pull-through strength of crest-fixed claddings, but may be ad-

equated for valley-fixed claddings.

4. The design formula (Equation 3) recommended by Mahendran (1994) is able to predict the local dimpling and pull-through strengths of the commonly used crest-fixed steel cladding systems with conventional screw fasteners. However, it does not include the effects of screw head/washer diameter and the profile geometry.
5. The local dimpling or pull-through failure loads were predicted well by the new improved formulae (both Equations 4(a) and 4(b)). However, Equation 4(b) with a capacity reduction factor of 0.60 is recommended for design purposes. The improved design formulae are applicable to only the commonly used profiled steel claddings shown in Figure 1. Further research is planned to extend the design formula to include relevant geometrical parameters.

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7 REFERENCES

1. American Iron and Steel Institute (AISI). Specification for the Design of Cold-formed Steel Structural Members. Washington, DC: Addendum, AISI, 1989.
2. American Iron and Steel Institute (AISI). Test methods for Mechanically Fastened Cold-formed Steel Connections. Report CF92-1, AISI. Washington, DC, 1992.
3. Beck VR and Stevens LK. Wind Loading Failures of Corrugated Roof Cladding. Civil Eng Trans, IE Aust, 1979;21(1):45-56.
4. Eurocode 3. Design of Steel Structures, Part 1.3 - Cold-formed Thin-gauge Members and Sheeting. Draft document CEN/TC250/SC3 - PT1A. Commission of the European Communities, August, 1992.
5. Macindoe L and Hanks P. Standard Tests for Cold-formed Steel Single Fastener Connections. Proc. of Australasian Structural Engineering Conference, Sydney, 1994:253-257.
6. Macindoe L, Adams J and Pham L. Performance of Single Point Fasteners. Report to the CRC for

Materials, Welding and Joining, CSIRO Division of Building, Construction and Engineering, Melbourne, 1995.

7. Mahendran M. Fatigue Behaviour of Corrugated Roofing under Cyclic Wind Loading. *Civil Eng Trans*, IEAust, 1990;32(4):219-226.
8. Mahendran M. Static Behaviour of Corrugated Roofing under Simulated Wind Loading. *Civil Eng Trans*, IEAust, 1990;32(4):211-218.
9. Mahendran M. Behaviour and Design of Crest-fixed Profiled Steel Roof Claddings under High Wind Forces. *Engrg Struct*, 1994;16(5).
10. Mahendran M. Towards an Appropriate Fatigue Loading Sequence for Roof Claddings in Cyclone Prone Areas. *Engrg Struct*, 1995;17(7):476-484.
11. Mahendran M. Test Methods for Determination of Pull-through Strength of Screwed Connections in Profiled Steel Claddings. *Civil Eng Trans*, IEAust, 1995;CE37(3):219-227.
12. Mahendran M and Tang RB. Pull-out Strength of Steel Roof and Wall Cladding Systems. Physical Infrastructure Centre, Research Report 96-38. Brisbane: Queensland University of Technology, 1996.
13. Pekoz T. Design of Cold-formed Steel Screw Connections. *Proc. of the Tenth International Specialty Conference on Cold-formed Steel structures*, St. Louis, Missouri, USA, 1990:576-587.
14. Standards Australia (SAA). AS1562 Design and Installation of Sheet Roof and Wall Cladding, Part 1: Metal, 1992.
15. Standards Australia (SAA). AS4600 Cold-formed Steel Structures Code, 1996.
16. Tang RB and Mahendran M. Pull-through Strength of Profiled Steel Cladding Systems. Research Monograph 98-6. Brisbane Physical Infrastructure Centre, Queensland University of Technology, 1998.
17. Toma A, Sedlacek G and Weynand K. Connections in Cold-formed Steel, Thin-walled Structures, 1993;16:219-237.
18. Xu YL. Behaviour of Different Profiled Roofing Sheets Subject to Simulated Wind Uplift. Tech Report No. 37. Townsville: James Cook University Cyclone Testing Station, 1994.